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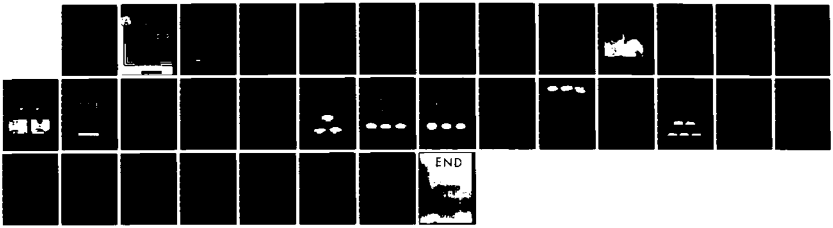

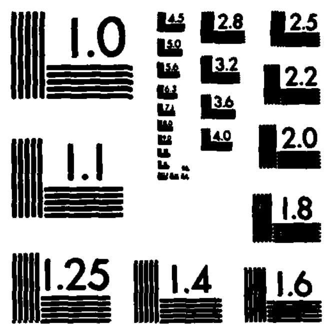

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USAARL REPORT NO. 84-8

AD-A144 179

ENERGY ABSORBING EARCUP ENGINEERING FEASIBILITY EVALUATION

By
Ted A. Hundley
J.L. Haley, Jr.

BIODYNAMICS RESEARCH DIVISION

July 1984

U.S. ARMY AEROMEDICAL RESEARCH LABORATORY
FORT RUCKER, ALABAMA 36362

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20. ABSTRACT

The concept of using the integral structure of a noise-attenuating earcup as a "load-limiting" or energy-absorbing device is explored in this report. The standard earcup of the Army's SPH-4 flight helmet is a very rigid structure which requires a force of approximately 22,000 newtons to cause it to deform, a force level three times greater than the crushing strength of the skull. Fifteen different "crushable" earcups were constructed and evaluated for noise attenuation to determine their suitability for prototype construction. Three earcups were selected for the "crushability" evaluation. The corrugated aluminum earcup was selected as the best of the three evaluated. The aluminum earcup was modified to lower the cost and to increase the crushing depth to nearly 2 cm. The feasibility of producing a "crushable" earcup with similar noise attenuation characteristics to the existing Army SPH-4 earcup was demonstrated.

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INTRODUCTION

The impact protection provided by the SPH-4 flight helmet has been effective in reducing the number of head injuries in aviation accidents. However, the protection against lateral impacts is very poor because no energy-absorbing material (foam) was used in the side of the SPH-4 (Haley, et al., 1983) (Figure 1). A study of helmets retrieved from Army aircraft accidents under the Aviation Life Support Equipment Retrieval Program (ALSERP) showed that lateral impacts resulted in a significantly higher rate of serious injury than did impacts to other regions (68% versus 40%) (Shanahan, 1983). By replacing the standard rigid plastic earcup with one designed to absorb impact energy, a significant reduction in head injuries can be obtained. Our goal was to establish the feasibility of an earcup design that would meet the acoustic attenuation, weight, and size requirements of the existing SPH-4 specification (MIL-H-43925A) while providing impact protection for the lateral area of the head. This report summarizes the initial efforts undertaken in pursuit of this goal.

FIGURE 1. Area of Cranium Coverage with the Standard Foam Liner of the SPH-4 Flight Helmet (Note the absence of foam at the sides)

METHODS AND MATERIALS

The first step taken was to select the design crush strength for the earcup. Available data on the fracture strength of the temporal area of the skull was very limited. Load levels for the temporoparietal region ranging from 2000 newtons (N) to 6000 N have been noted by several researchers (Gurdjian, Lissner, and Webster, 1974, Schneider and Naham, 1972, and Travis, Stalnaker, and Melvin, 1977). The wide range of values, based on cadaver skull laboratory impacts onto surfaces as small as 6.5 cm^2, provided some data from which to estimate a "crushing" load limit for the earcup. Since the existing SPH-4 earcup design covers an area of 79 cm^2, a relatively high value of 4500 N was selected. A lower level probably would insure no skull fracture, but the crush depth would increase beyond the 2.3 cm available in the SPH-4 helmet. Simply stated, this crushable level was required if the earcup area of the helmet was to absorb as much energy as other areas of the helmet without exceeding the impact (concussion) tolerance of the head.

A contract was let to Simula, Inc., to produce a number of prototype earcups. The task assigned to them was to design and build a prototype earcup which would meet the following requirements:

a. Must fit in the available earcup space of the existing SPH-4 helmet.

b. Must provide acoustic attenuation equal to the SPH-4 helmet specification.

c. Must be compatible with existing SPH-4 communication system.

d. Weight of each earcup must not exceed 99 g.

e. Must crush at a load of 4500 N.

f. Must be durable enough to withstand normal environmental exposure.

g. Must not be prohibitive in cost.

h. Pressure buildup during earcup crushing must be limited to prevent eardrum rupture.

Upon completion of the contract, Simula, Inc., delivered a report (Warrick and Svoboda, 1981) in which the earcup prototype development was described. The report said that a tradeoff study was done on 15 different materials. The three materials selected for prototype evaluation as earcup structure were: (a) closed-cell plastic foam, (b) aluminum honeycomb, and (c) convoluted aluminum sheet. These materials appeared to offer the best opportunity of achieving optimum energy absorption and acoustic attenuation with minimal weight and cost.

Acoustic attenuation was evaluated by placing an aluminum cylinder containing a calibrated microphone in a semireverberant room with a sound system capable of producing a continuous broadband noise field with a frequency range of 16 to 20,000 Hz. The output of the microphone without an earcup in place was compared to output with an earcup in place to determine the amount of acoustic attenuation present (Figure 2). To eliminate possible reproducibility problems, no earseals were used. The 15 earcup prototypes were bonded adhesively to an aluminum plate which in turn was bolted onto the aluminum cylinder containing the microphone. An O-ring provided an effective acoustic seal between the plate and the aluminum cylinder. The earcups were made in the form of a right circular cylinder of approximately the same internal volume as the standard SPH-4 earcup. This configuration provided a usable comparison of acoustic attenuation capability of the 15 design variations examined and was lower in cost than producing an oval shape similar to the standard earcup.

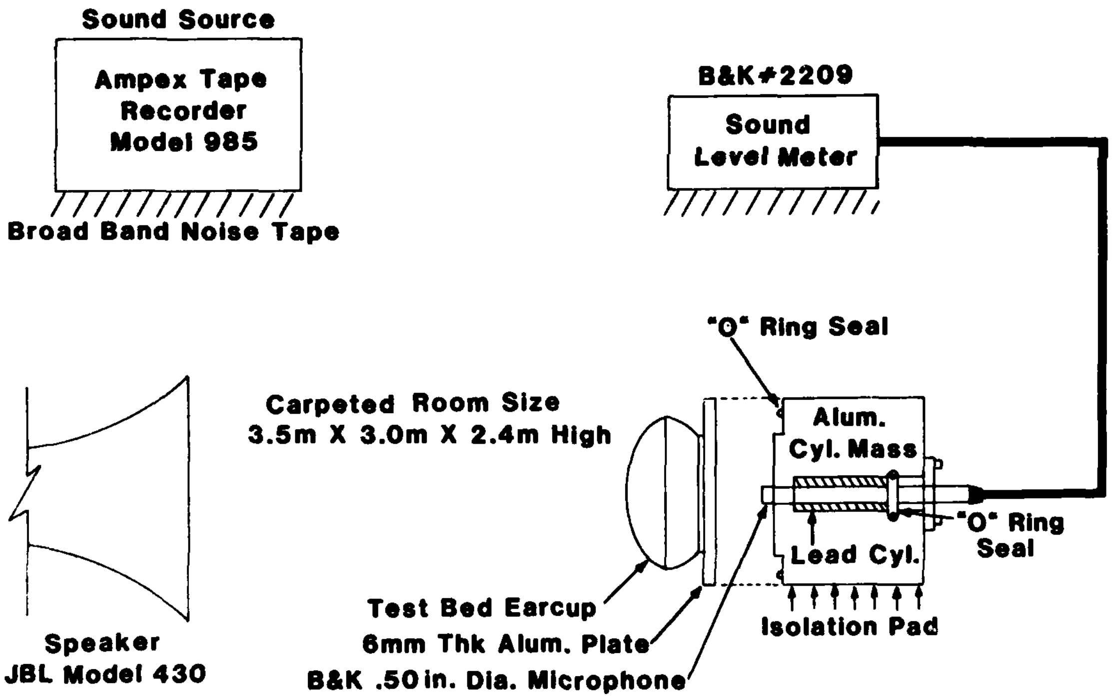


FIGURE 2. Test Setup used by Simula, Inc. to Screen the 15 different Earcup Materials

On the basis of these comparison tests, three candidate materials, with acoustic attenuation performance within the criteria of MIL-H-43925A, were selected. Prototype earcups of the three candidate materials were fabricated and sent to the US Army Aeromedical Research Laboratory (USAARL) for testing (Figure 3).

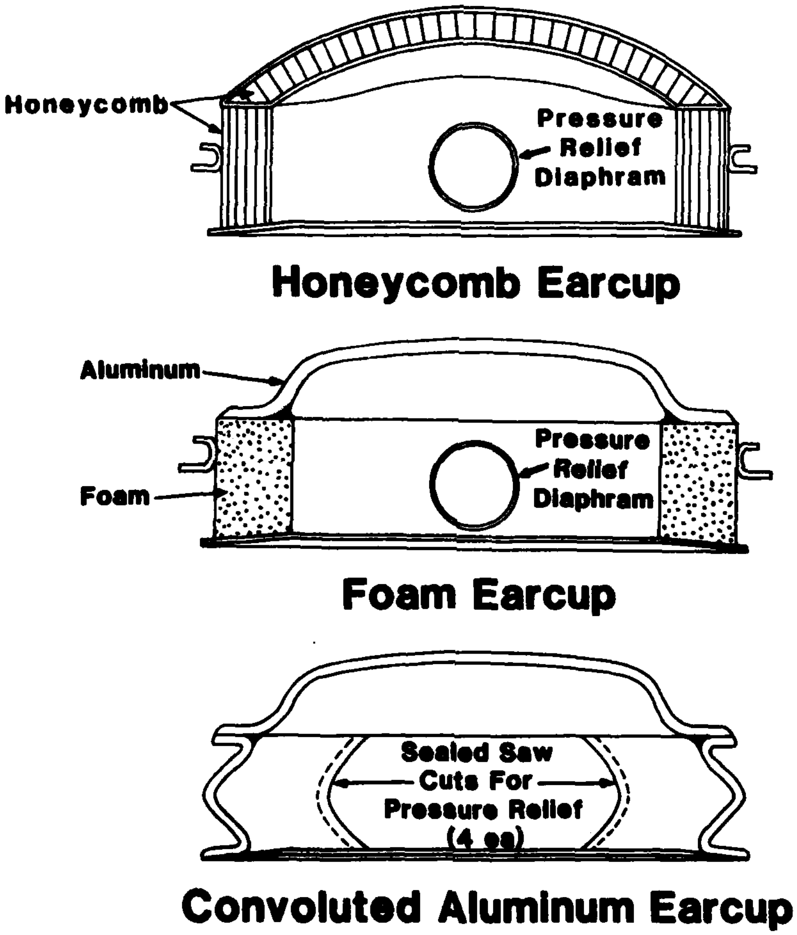


FIGURE 3. Energy-Absorbing Earcups (Cross Section View)

Upon receipt of the earcups, static crush tests of the prototype and standard earcups were conducted using the Tinius-Olsen universal test machine.* Each earcup, complete with earseal, was placed on a flat steel plate on the test machine base. The standard SPH-4 cup configuration is shown in Figure 4. A segment of the earcup bulge of the SPH-4 shell was cut off and placed on top of the earcup to simulate the SPH-4 load distribution (Figures 4 and 5). The earcup then was compressed at a rate of 2.5 cm/minute. The results of the static crush test provided a means of determining the ability of each earcup to dissipate kinetic energy.

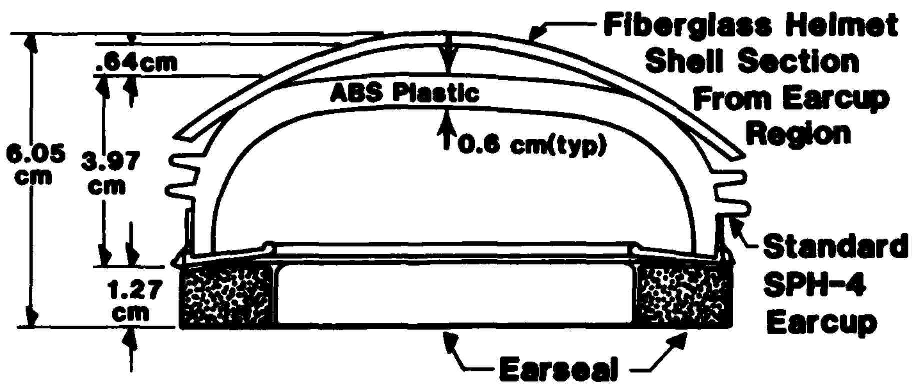


FIGURE 4. Standard SPH-4 Earcup Cross Section, as Tested (Crushable earcups use identical helmet shell section and earseal)

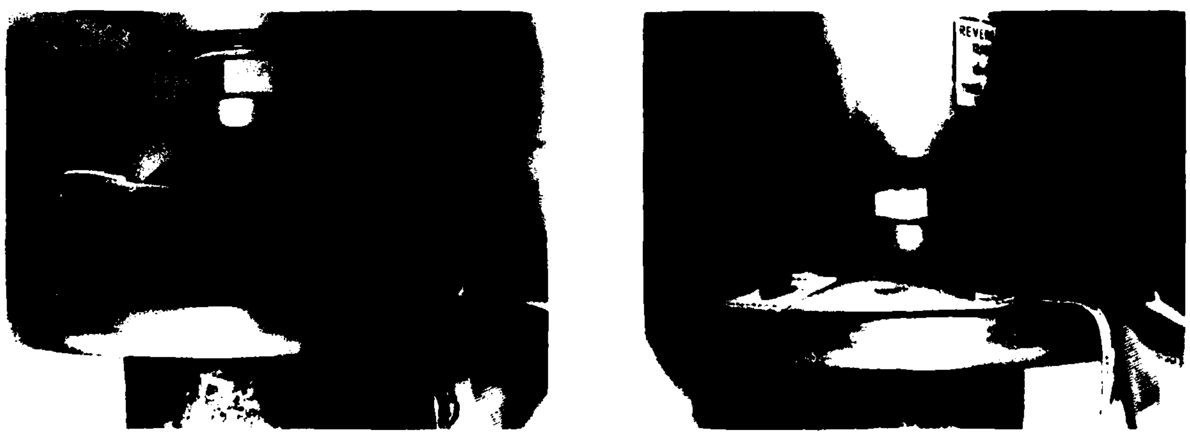
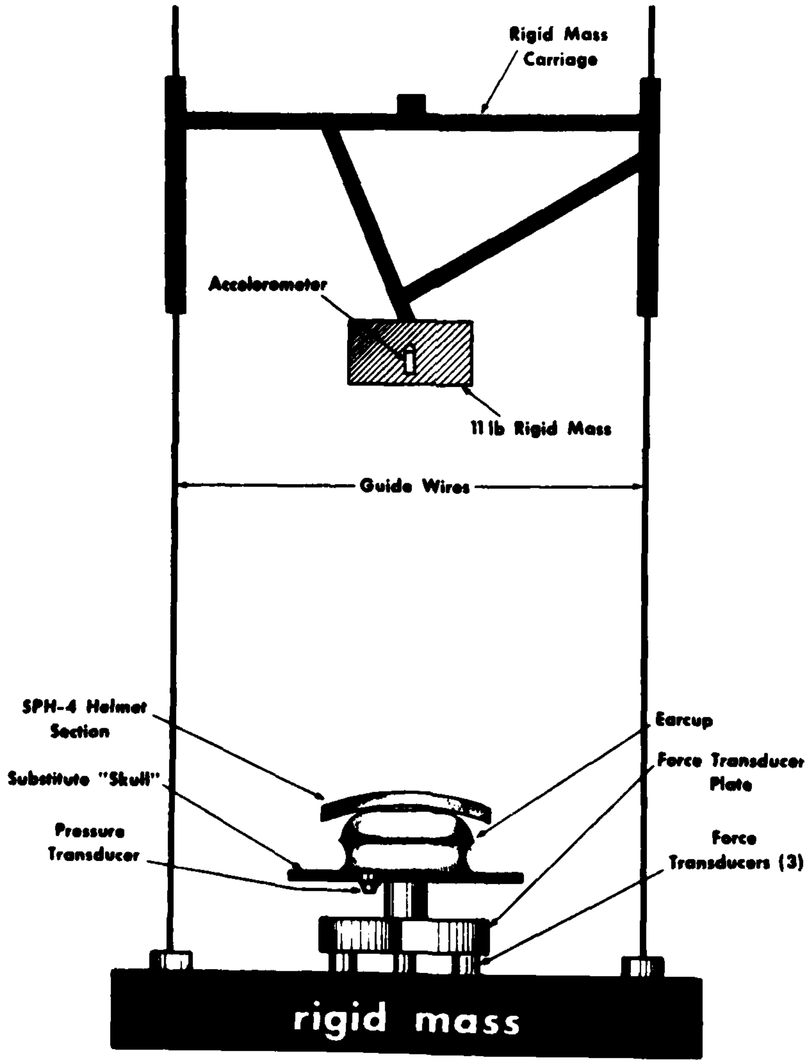


FIGURE 5. Before and After View of Static Earcup Crush Test

Next, dynamic crush tests were conducted to evaluate the loading rate effect on internal pressure and transmitted load to the skull. Testing was done on the USAARL helmet drop tower as shown in Figure 6. The guide wires, headform carriage, headform, accelerometer, and drop tower mass conform to American Standard Association Z90.1 specifications. A piezoelectric accelerometer was used in the headform to measure acceleration for comparison with the force measurement. The transducers' outputs were displayed on a Nicolet model 2090 two-channel digital oscilloscope*, recorded on a Hewlett-Packard model 3960 FM tape recorder*, and transmitted to an Electronics Associates, Inc., analog computer model 681* for processing and digitized with a SYSTEMS 85 digital computer for data reduction and analysis.



Earcup Test Set-up

FIGURE 6. Test Setup for Earcup Impact Test

Each earcup with earseal was placed on a flat metal plate supported by a load cell. A threaded hole in the plate contained a pressure transducer so that the dynamic pressure rise caused by the crushing of the earcup and the compression of the earseal could be measured. Each earcup was covered by a segment of the helmet shell to simulate the actual load distribution. The impacting surface was the relatively flat crown portion of the bare metal headform which weighed 4.99 kg, including the carriage.

The headform and carriage were raised to a height sufficient to generate 70 N·m of kinetic energy and then dropped onto the earcup as shown in Figure 6. Not enough earcup crushing was obtained at this energy level, so the drop height was increased enough to generate 90 N·m of kinetic energy for the remaining tests recorded in this report.

The review of the internal pressure change due to the volume change inside the earcup was informative. The pressure increased to 65 kilo Pascal (kPa) minimum. This pressure is more than twice the level required for rupture of the ear's diaphram (James et al., 1982). Although the pressure venting devices in the earcups were opening, the time of opening occurred after the internal volume of the earcup and seal was reduced by 40 percent. This large volume change prior to pressure relief is caused primarily by the earseal's compression depth of one cm prior to collapse ("crushing") of the relatively rigid earcup.

Since all three prototype earcups were designed to relieve pressure as a result of structural deformation of the earcup proper, it was clear that the integral pressure venting would not occur until the earcup was crushed and that the earcup would not crush until the earseal was compressed; i.e., the integral pressure venting would not activate until after the pressure had exceeded 20-30 percent of atmospheric pressure--man's tolerable limit.

Notwithstanding the pressure increase problem, no change was made in the prototpye development effort because a reliable, low-cost, light-weight, and small-volume pressure venting device was considered beyond the scope of this effort.

Review of the impact data for the three earcups revealed the best performance for the aluminum earcup. The second phase of this effort was begun by contracting with Simula, Inc., to produce a quantity of the crushable aluminum earcups for additional testing. The design was modified by Simula to make production easier as shown in Figure 7.

The earcup was formed from 1-mm thick 6061-0 aluminum. After forming, the earcup was heat-treated to a T6 hardness level. Slots of 0.25-mm width and 28-mm length were machined into the sides of the earcup shell to improve the crushing performance of the earcup shell and to provide a pressure venting mechanism. The slots were sealed with enamel paint to maintain an acoustically sealed enclosure. A metal cap with four tangs were bonded adhesively to the top of the earcup to provide a method of attaching the earcup to the helmet harness.

Upon receipt of the redesigned aluminum earcups, the static and dynamic crush tests were repeated to verify that the performance of the redesigned earcup was acceptable. A cadaver test program then was begun to verify that the crushing load of the earcup did not exceed human tolerance. The cadaver test program is described in USAARL Report 83-14, titled "Impact Response of an Energy Absorbing Earcup" by Shanahan and King, 1983.

RESULTS AND DISCUSSION

STATIC TESTS

The results of the static crush tests are depicted in Figure 8. The standard SPH-4 earcup was very rigid with the failure load reaching 20,000 N. The crushable earcups did not exceed 6000 N until after they had been crushed through a total distance of 2.0 cm. The convoluted aluminum earcup performed best with the honeycomb earcup a close second. The crushable foam earcup was the least efficient as its loading curve approximated an exponential increase as a function of crushing distance; the load should increase rapidly to the design load and then maintain that load through the available crushing distance for maximum efficiency. The convoluted aluminum earcup came closest to the "limit" load level with an average crushing load of 4000 N through a total distance of approximately 1 cm.

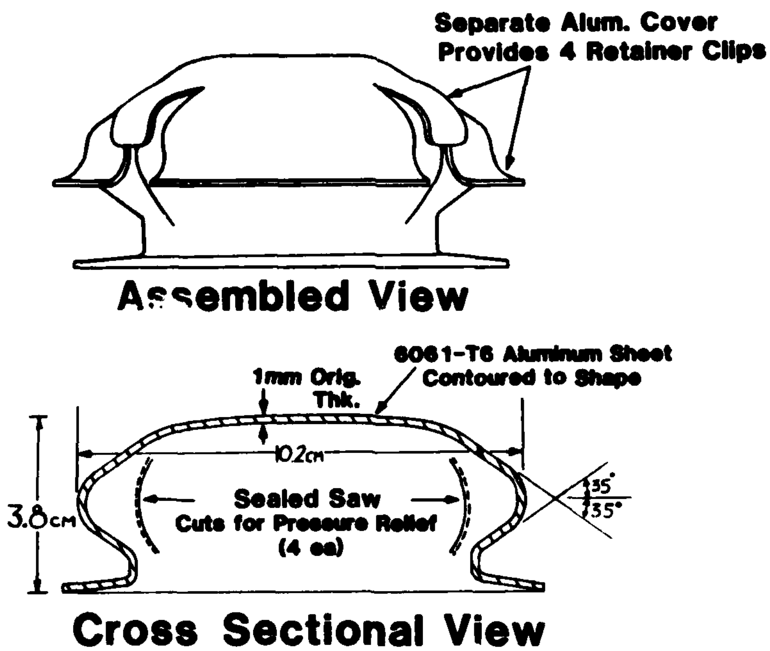


FIGURE 7. Crushable Aluminum Earcup as Redesigned by Simula, Inc.

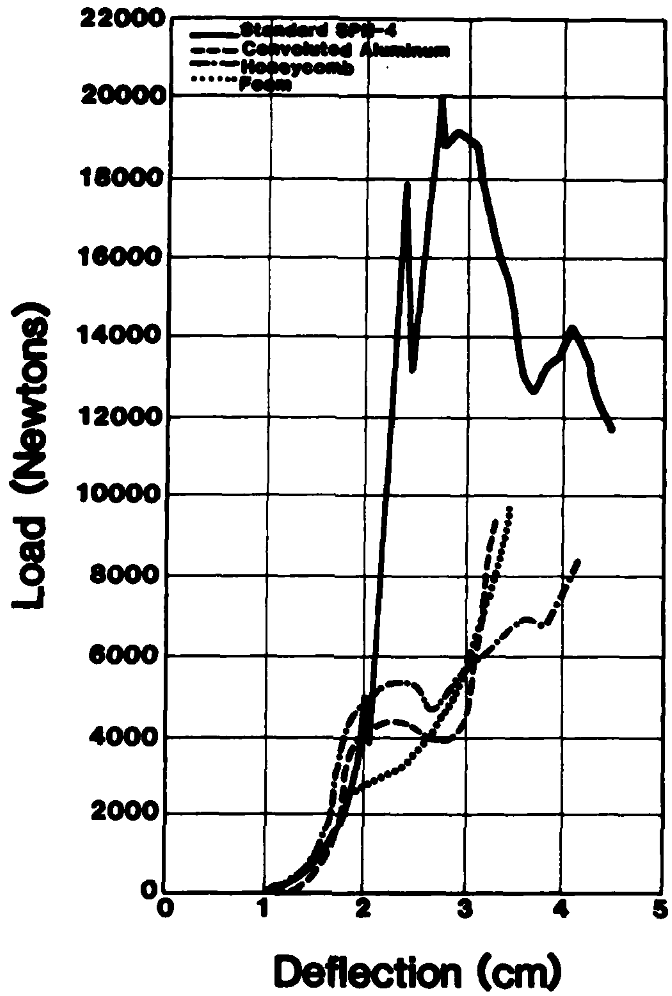


FIGURE 8. Earcup Load Versus Deflection in Static Crushing Test

DYNAMIC TESTS

The first dynamic tests were done from a drop height of 1.43 meters which resulted in a kinetic energy level of 70 N·m. The honeycomb earcup was tested first. The recorded peak force was 9620 N, but this peak was reached because of "ringing" in the load cell as shown in Figure 9. After filtering the data, the peak recorded was 6400 N and the peak pressure was 71.3 kPa. Examination of the earcup showed that the specimen was not totally crushed (Figure 10). Thus, the drop height was increased to 1.84 meters or to 90 N·m energy for the remaining tests. The honeycomb earcup was not tested at 90 N·m energy due to the limited number available.

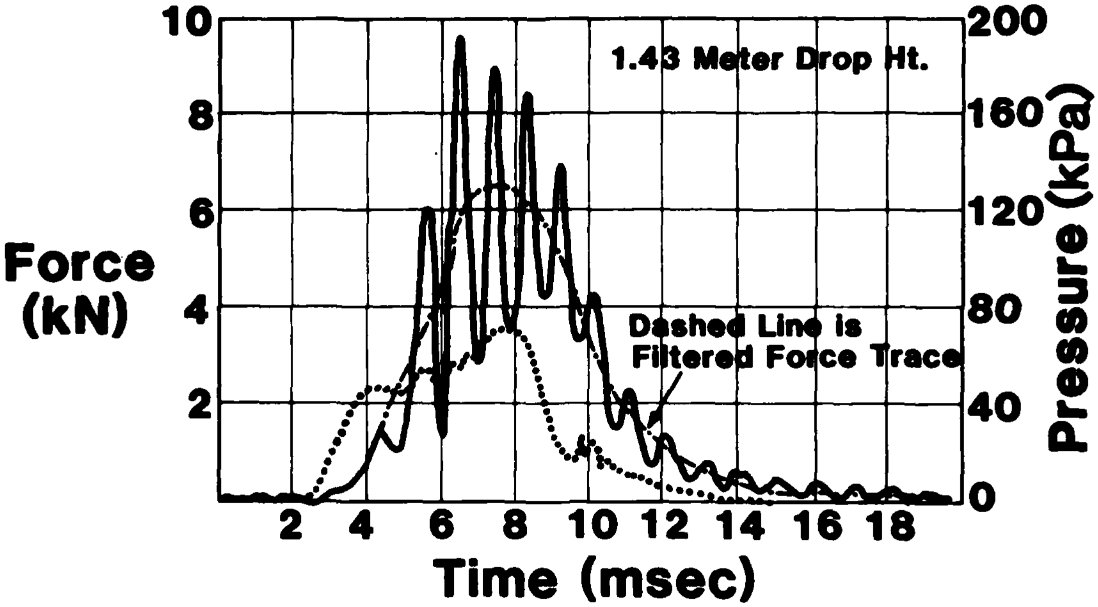


FIGURE 9. Dynamic Crushing Load and Pressure Rise of Honeycomb Energy-Absorbing Earcup

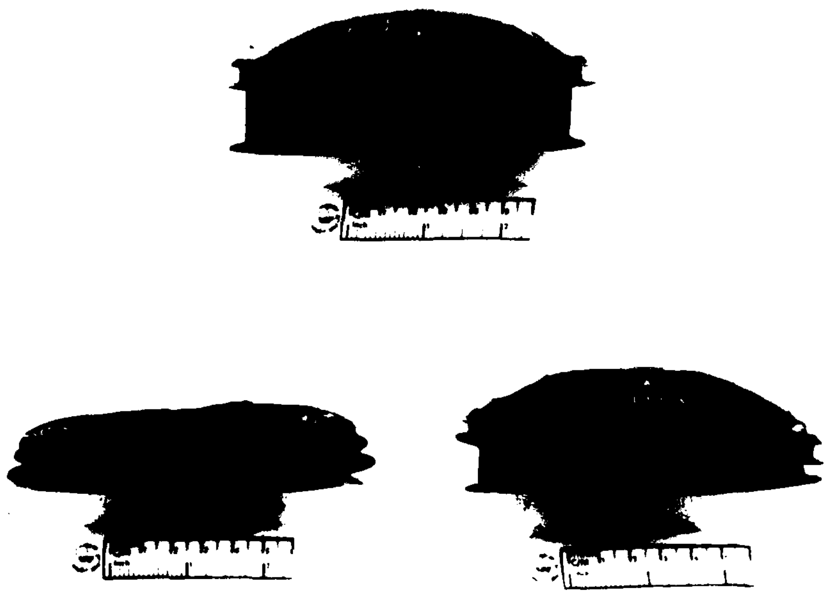


FIGURE 10. Simula Honeycomb Energy-Absorbing Earcup Before and After Testing

The measured peak force was 5790 N for the polyurethane foam earcup as shown in Figure 11. After filtering to eliminate the "ringing," the peak force was 5100 N. The peak pressure was 93.6 kPa. Examination of the earcup after the test showed an acceptable amount of symmetrical crushing (Figure 12).

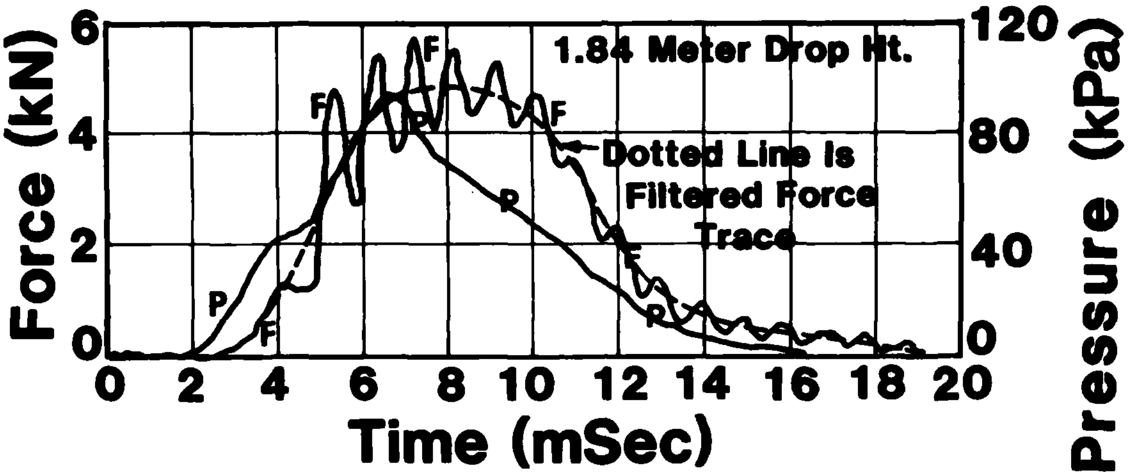


FIGURE 11. Dynamic Crushing Load and Pressure Rise of Foam Energy-Absorbing Earcup

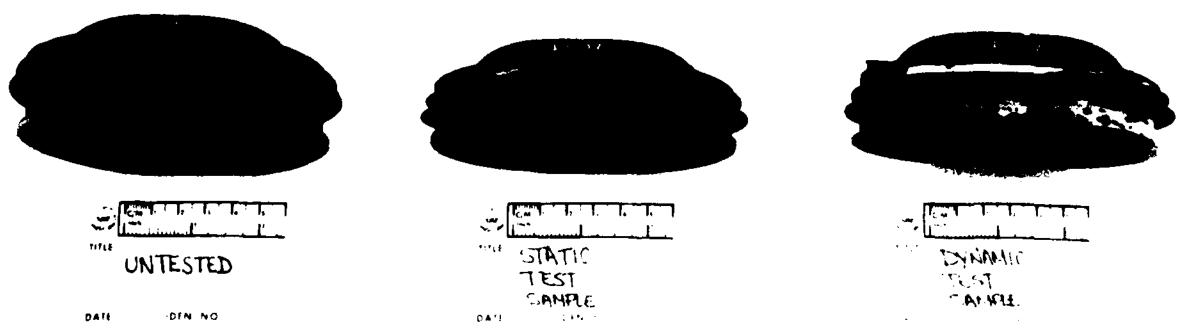


FIGURE 12. Simula Foam Energy-Absorbing Earcup Before and After Testing

To minimize the "ringing" in the force trace, the strain-guage type transducer with a 1000 Hz resonant frequency was changed to a force transducer with 3000 Hz resonant frequency. The replacement transducer consisted of three Kistler 902A piezoelectric load washers* mounted under a 2.5-cm thick triangular aluminum plate. This new load transducer reduced the "ringing" problem to an acceptable level.

The convoluted aluminum was tested next; the measured peak force was 5840 N as shown in Figure 13. The peak pressure was 94.4 kPa. A reasonably consistent load was maintained throughout the crushing. The earcup crushed symmetrically as shown in Figure 14.

*See Appendix A

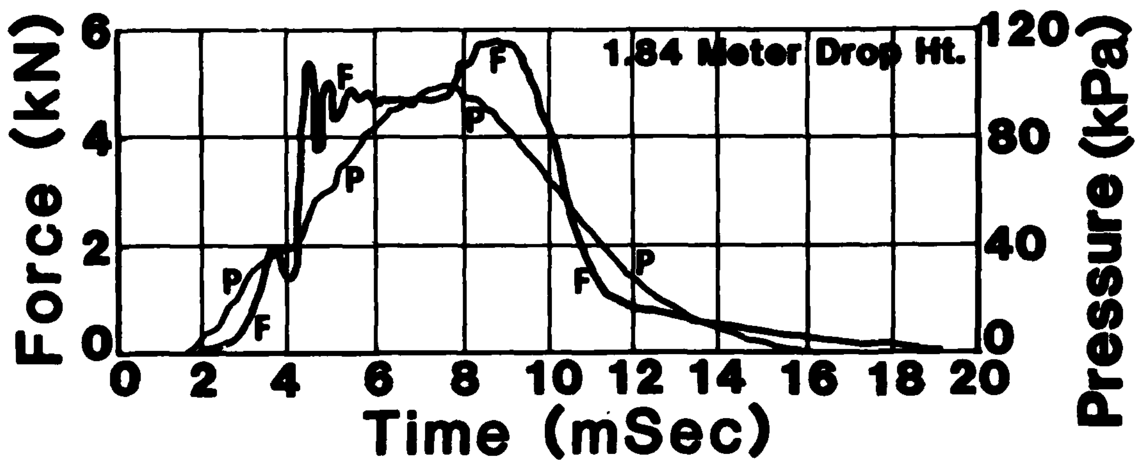


FIGURE 13. Dynamic Crushing Load and Pressure Rise of Convoluted Aluminum Energy-Absorbing Earcup

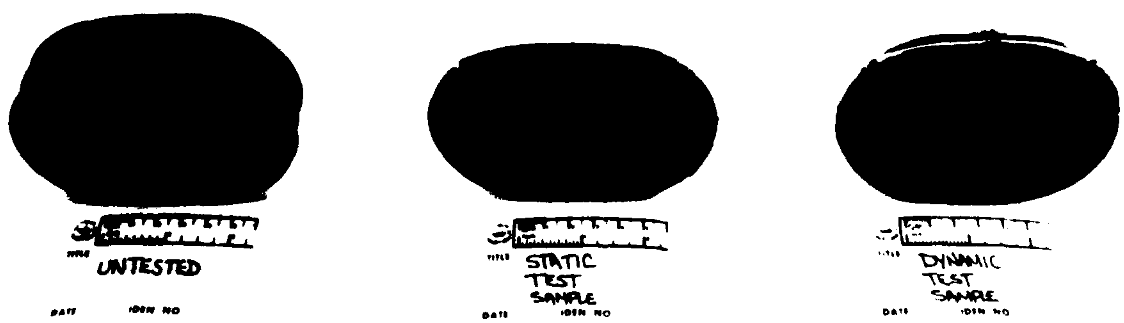


FIGURE 14. Simula Convoluted Aluminum Energy-Absorbing Earcup Before and After Testing

For comparison, a standard SPH-4 plastic earcup also was impacted. The measured peak force was 22,400 N as shown in Figure 15. The peak pressure was 65.0 kPa. No visible damage to the earcup could be detected after the test. The damage done to the earcup during static testing is shown in Figure 16. The cracking-type failure usually is a catastrophic event that occurs suddenly when the failure load is reached. If the load is removed prior to failure, no significant damage can be detected. The dynamic loading behavior of the convoluted aluminum earcut is compared to the standard SPH-4 earcup in Figure 17. The superior performance of the convoluted aluminum earcup in limiting the transmitted force and doing work to absorb the kinetic energy is clear.

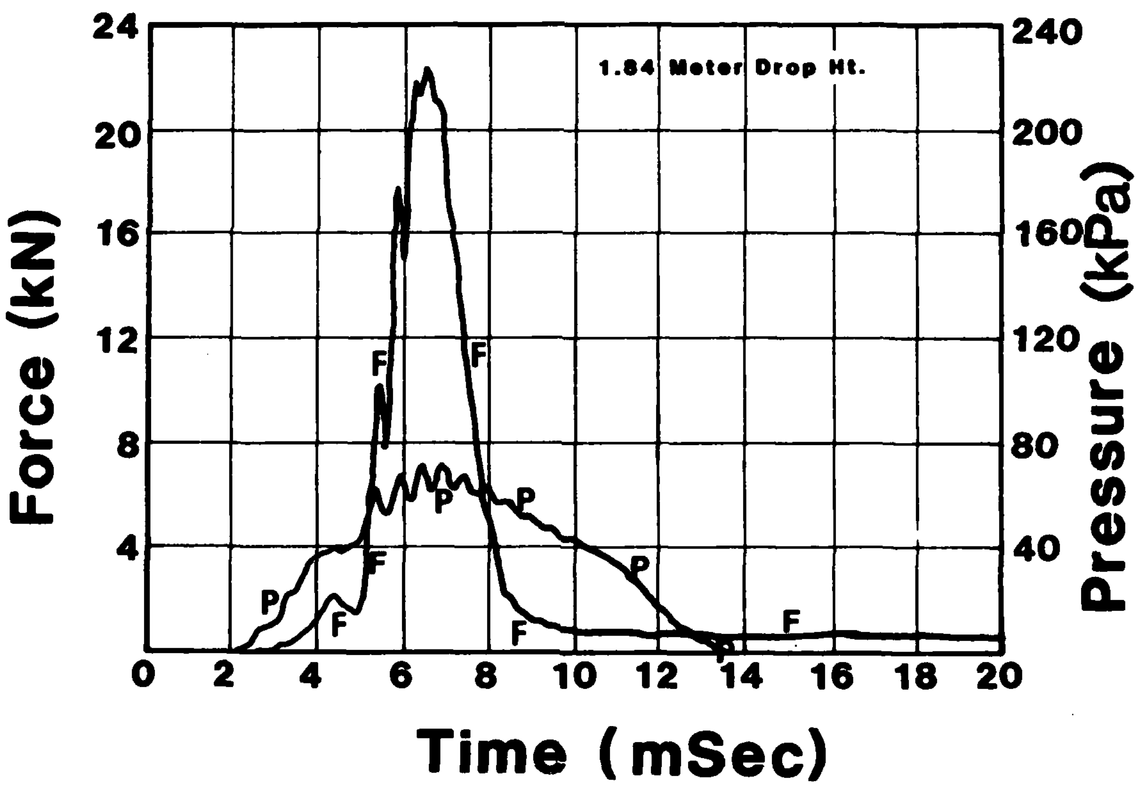


FIGURE 15. Dynamic Crushing Load and Pressure Rise of the Standard SPH-4 Earcup

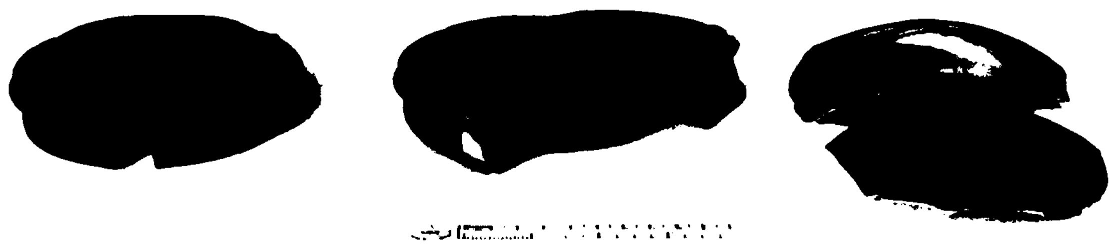


FIGURE 16. Damage Done to the Standard Gentex SPH-4 Earcup During Static Testing

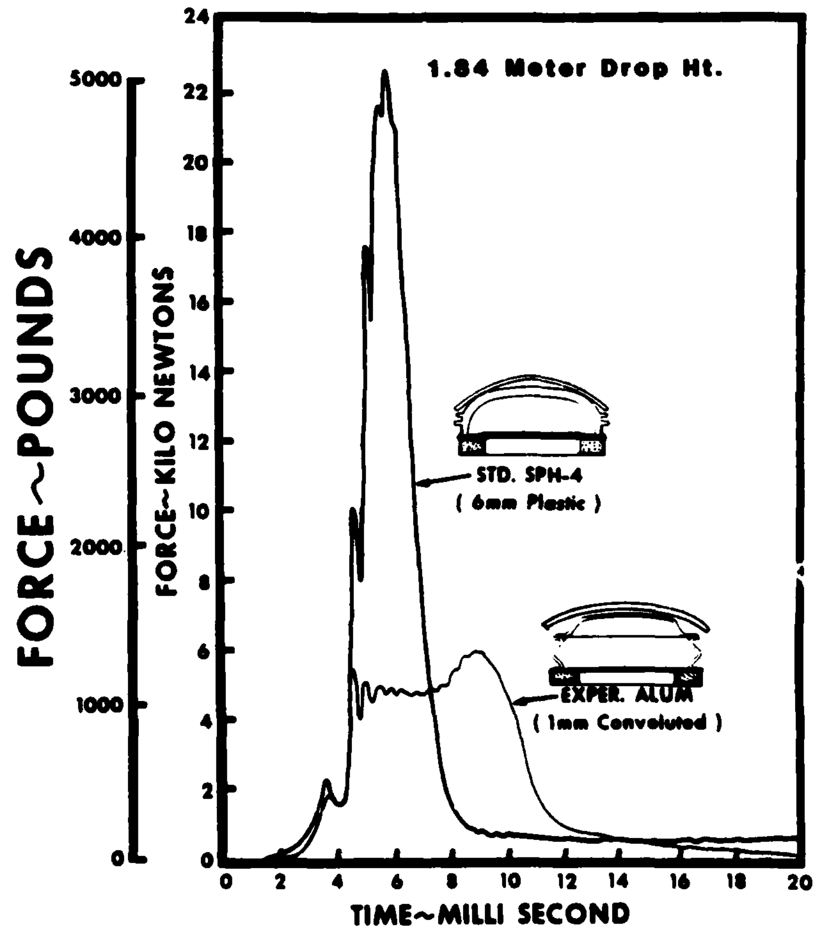


FIGURE 17. Comparison of the Dynamic Loading Performance of the Convoluted Aluminum Earcup and the Standard SPH-4 Earcup

Analysis of the high speed film showed that the pressure vents were opening at approximately 7 msec after the headform touched the earcup. This was too late to prevent the internal pressure from exceeding the desired 30 kPa limit which is the assumed pressure at which the normal human eardrum will rupture (James et al., 1982). Compression of the earseal alone is enough to raise the internal pressure above the rupture level. Nonetheless, the vent does shorten the time duration and the peak pressure (if crushing occurred without venting); thus, the vent is deemed desirable.

After completion of this testing, the convoluted aluminum earcup design was selected as the best performer on the basis of simplicity, load limit performance, and probable reliability in service. Simula, Inc., then modified the design to improve the producibility. The producibility changes included a change in contour to provide more stroke and a reduction in the aluminum thickness to 1.0 mm. The redesigned earcups were produced and sent to USAARL for evaluation.

Upon receipt of the redesigned earcups, the static and dynamic crushing tests were repeated. The static crushing performance of the redesigned earcup was improved with approximately 1 cm of extra crushing distance as shown in Figure 18. The dynamic crushing performance also showed some improvement as shown in Figure 19. The degree of dynamic crushing for five energy levels from 41 N•m to 95 N•m for the redesigned earcup is illustrated in Figure 20.

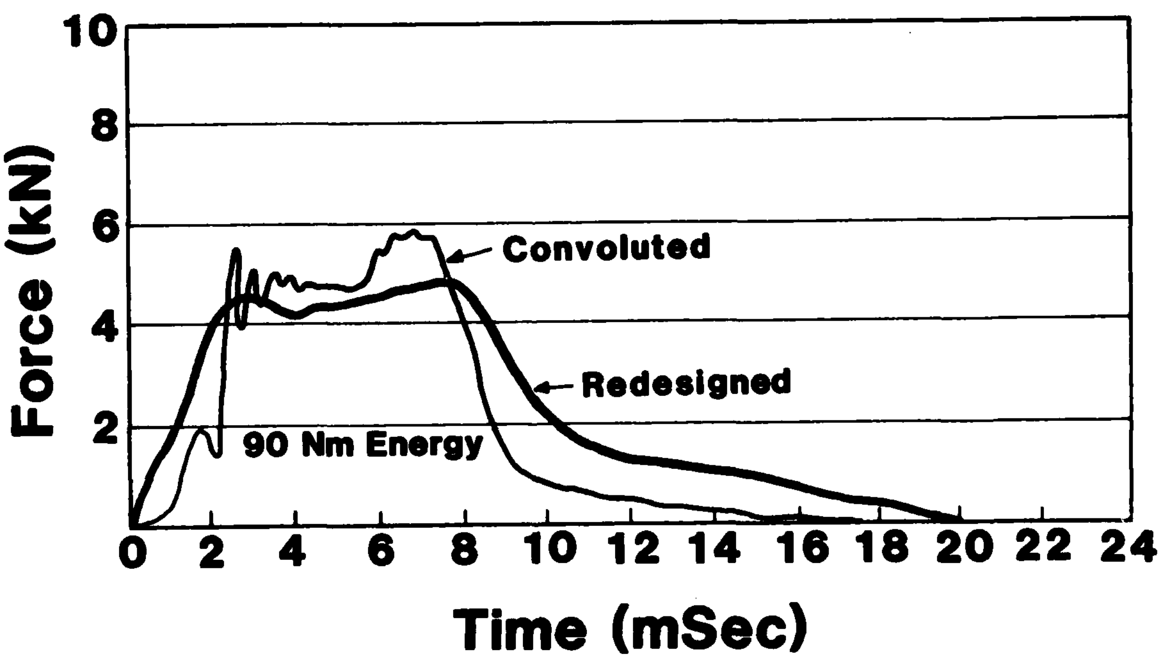


FIGURE 18. Comparison of Static Crushing Performance of Redesigned Earcup and Convoluted Earcup

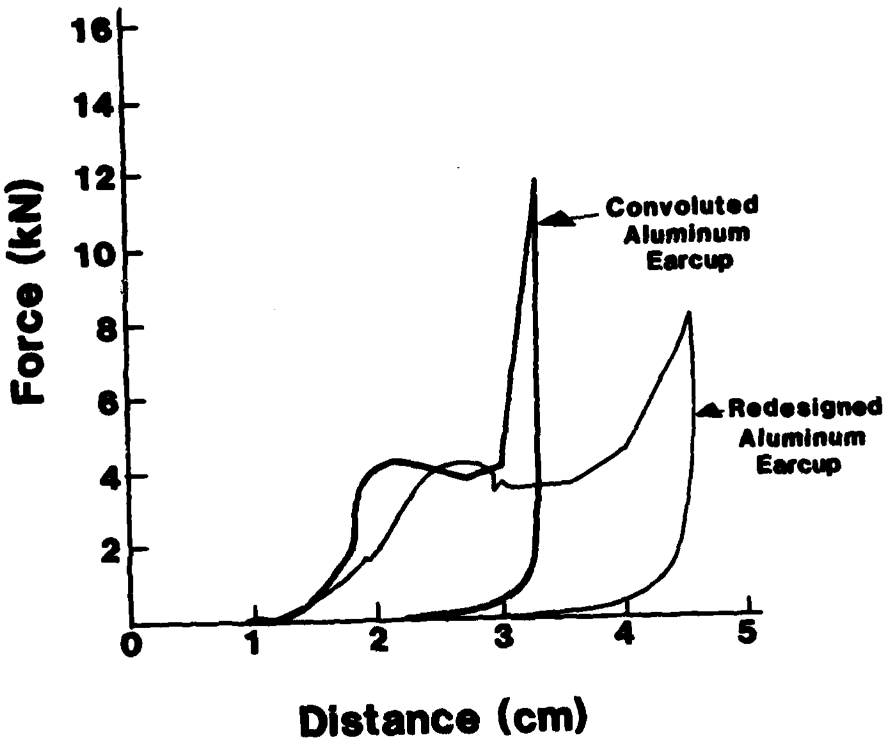


FIGURE 19. Comparison of the Dynamic Crushing Performance of the Convoluted *Aluminum Earcup and the Redesigned Aluminum Earcup*

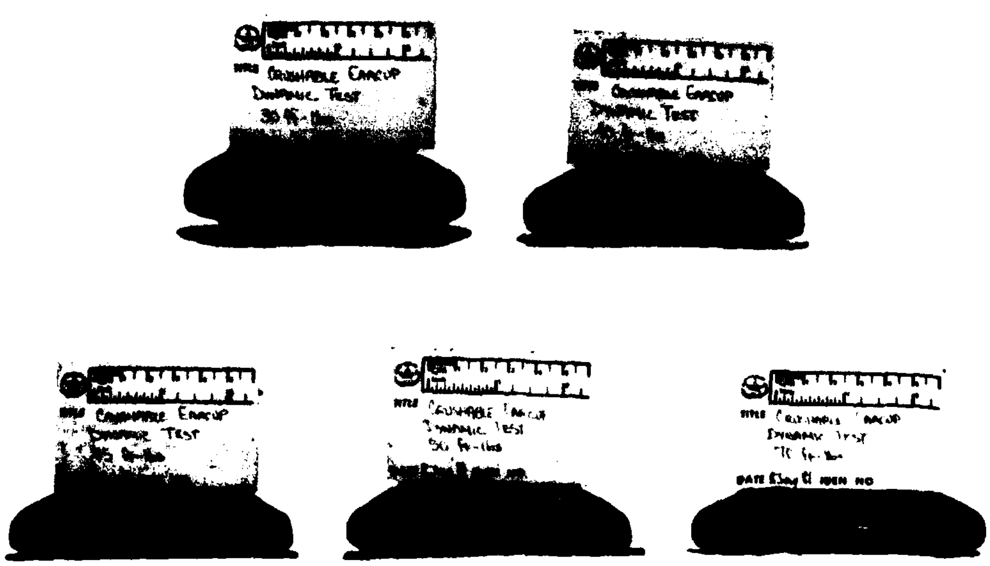


FIGURE 20. Degree of Crushing Shown for Various Energy Impacts

CONCLUSIONS

It is concluded that:

1. A need exists for an energy-absorbing earcup.

2. An energy-absorbing "crushable" earcup can be built with existing technology and within the limitations imposed by the existing helmet and acoustic protection requirements.

RECOMMENDATIONS

It is recommended that:

1. All impact-protective helmets containing large volume (circumaural type) earcups be provided with an integral energy-absorbing mechanism in the earcup structure.

2. Energy-absorbing earcups should be procured for retrofit to all inventory flight helmets and for inclusion in all future flight helmets.

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APPENDIX A

LIST OF TRADE NAME EQUIPMENT

Electronic Associates, Inc.
185 Monmouth Parkway
West Long Branch, NJ 07764

Model 681 analog computer

Hewlett-Packard
2000 South Park Place
Atlanta, GA 30339

Model 3960 FM tape recorder

Kistler Instrument Corp.
75 John Glenn Tr.
Amherst, NY 14120

902A piezoelectric load washers

Nicolet
3902 Casaba Loop
Valrico, FL 33594

Model 1090 two-channel digital oscilloscope

Simula, Inc.
2223 S. 48th Street
Tempe, AZ 85282

Prototype earcups

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Department of the Navy
Washington, DC 20361

US Navy
Naval Research Laboratory Library
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US Navy
Naval Research Laboratory Library
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Structures Laboratory Library
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NASA Langley Research Center
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US Navy
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US Air Force
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US Army Yuma Proving Ground
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US Air Force
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US Navy
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US Army Combat Developments
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